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TACTICAL MISSILE TURBULENCE PROBLEMS

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1. INTRODUCTION

Recently, the Missile Command acquired two new project offices: Remotely Piloted Vehicles (AQUILA) and Unmanned Aerial Vehicles. Usually, missile and rockets do not bank to turn so we are playing catch-up on winged vehicles.

Our usual bill of fare consists of free flight rockets and guided missiles. They range from direct fire systems to tactical ballistic missiles, with air defense thrown in for good measure.

Add to the above smart and dumb submunitions, and it is readily apparent that our interest is from the surface to the exoatmosphere. Of particular interest is atmospheric turbulence in the atmospheric boundary layer, since this affects both the launch and terminal phase of flight, and the total flight for direct fire systems.

2. ROCKET ARTILLERY BOOST WIND PROBLEMS

Rocket artillery, being unguided, is unable to correct for the effects of winds after launch. Cannon artillery is boosted in the tube, while rocket artillery is boosted outside the tube. When a rocket comes out of the launch tube it is moving rather slowly. Any crosswind will cause an aerodynamically stable rocket to cock into the crosswind; then the propulsion will drive the rocket upwind. All the wind has to do is turn the rocket; the propulsion does the rest. Most of this effect occurs in the rocket's first yaw wavelength, about 20 to 200 m, depending on the rocket's characteristics.

One technique to reduce this effect is to reduce the aerodynamic stability by delaying the opening of the fins till the rocket is going faster. Since neutrally stable rockets also have their problems, the time delay is chosen to trade off various error sources.

3. MEAN WIND CORRECTION

With tube artillery, a forward observer may adjust the fire onto the target. This is not practical for rocket artillery since the targets are deep in the enemy's territory. The Swiss company Contraves has developed the FIELDGUARD fire directing radar which is used by the Federal Republic of Germany (FRG) with their 110 m Light Artillery Rocket System (LARS).

The FIELDGUARD radar tracks three registration rounds to the target area and adjusts fire like a forward observer. Due to the time of flight of the

rocket to the target, the FIELDGUARD can only reduce the effect of mean winds during boost and coast. Coast wind effects and wind effects after burnout are the same for rocket and cannon artillery.

4. TURBULENT BOOST WIND CORRECTION

The effects of turbulence during the first yaw wavelength are not corrected by FIELDGUARD. It has been proposed [1] that each round be tracked over the first yaw wavelength and this information then be used to correct the aiming of the next round. This is referred to as the Dynamically Aimed Free Flight Rocket (DAFFR) concept.

The coast wind effects could have already been determined by FIELDGUARD, or a MET message could be used as is done with tube artillery.

Of course, the ability of the DAFFR scheme to reduce the effects of turbulence during boost depends upon the correlation of turbulence over time [2,3] and the time between rounds.

The turbulence intensity which is a function of surface roughness can be quite large near the earth's surface. Cannon cockers like to fire from the tree line for concealment. The failure to consider surface roughness in the selection of rocket artillery launch sites could adversely affect system performance, particularly if that performance was determined in a benign turbulence environment. White Sands Missile Range could be considered a rather benign turbulence environment when compared with forested, mountainous, or urban regions of Europe.

5. THE DAFFR WIND FILTER

Assuming the longitudinal wind, u, is the sum of the mean wind, $\bar{u}$, and the turbulent wind, u', one has [2]:

$$u(t) = \bar{u} + u'(t)$$

The turbulent wind is related to its value at some previous time by [2]:

$$u'(t + \tau) = \rho(\tau)\, u'(t) + u''(t + \tau)$$

where ρ is the correlation coefficient for a time delay, τ, and u'' is the random component of the turbulence. The variance of the random component is defined by the relationship [2]:

$$\sigma^2(u'') = \sigma^2(u')[1 - \rho^2(\tau)]$$

so that the turbulent energy is conserved with time.

With this wind model, it was possible to develop a discrete recursive filter, Figure 1. First, a discrete Kalman filter was developed and then the Kalman filter gains were simplified to a set of suboptimal gains (Figure 1).

The gain for the mean, $1/n$, should be quite familiar. The gain for turbulence, $(1 - 1/n)$, is reduced by epsilon to take into consideration the effects of the random component of the turbulence and measurement noise. Since the rocket is being used to sense the wind, its randomness constitutes measurement noise.

6. THE DAFFR TEST

The DAFFR concept, with a FIELDGUARD on loan from FRG, was demonstrated at Eglin Air Force Base, Florida, in the spring of 1983 and 1984.

Two equipment problems were encountered. The first was ionization in the rocket exhaust plume that attenuated the DAFFR radar signal to such an extent that tracking had to be delayed until after burnout. No tracking data were available during the first yaw wavelength. The second and more severe problem was the slowness of the "surplus" launcher drives to re-aim. The time between rounds was approximately 6 seconds while 2 to 3 seconds was desired.

Even at 6 seconds between rounds, some improvement (10 percent) was noted. More importantly, that improvement was in good agreement with the preflight prediction for a 6-second delay. It is hoped that with 2 or 3 seconds between rounds, a reduction of turbulence boost effects of 50 percent could be achieved.

An interesting adjoint to the test was Lockheed's Active Infrared Measurement (AIM), a laser Doppler velocimeter. Though used during the DAFFR test as range instrumentation to measure boost winds, Lockheed contends the AIM could be used to measure the wind prior to the launch of each round and correct aim based upon those measurements. There is no one best answer.

7. ROCKET WAKE TURBULENCE PROBLEMS

During boost, the exhaust plume forces the airflow around the rocket away from the rear of the rocket. This reduces the aerodynamic effectiveness of fins placed at the rear, thus reducing the stability.

Another problem of interest is wake interference. Following rockets cut across the exhaust plume of leading rockets if they are too close in space and time. The effect decays quite rapidly (in seconds) but it does limit how close together rockets may be fired. During the DAFFR test, Lockheed's AIM did sense the wake and its decay. The effect is not well understood.

8. CONCLUSIONS

Of course, many of the turbulence problems of rockets and missiles are common to those of aircraft, such as structural loading and control system design. This discussion has been primarily about a problem peculiar to free flight rockets, which has not been solved at this time.

Besides the correlation of turbulence over time, the correlation over space is also of interest. What relationship do measurements of wind at the launcher have to winds in front of the launcher? What effect does turbulence have on the impact angle of dumb submunitions?

Each new system will have new turbulence problems associated with it.

REFERENCES

1. McCorkle, Jr., W. C.; and Lilly, J. A.: An Adjusted Fire Technique for a Highly Accurate Free Flight Rocket Artillery System, U.S. Army Missile Command Technical Report RD-74-13, Redstone Arsenal, Ala., June 1974.

2. Hanna, S. R.: Some Statistics of Lagrangian and Eulerian Wind Fluctuations, *Journal of Applied Meteorology*, 18:518-525, April 1979.

3. Frost, W.; Long, B. H.; and Turner, R. E.: Engineering Handbook on the Atmospheric Environmental Guidelines for Use in Wind Turbine Generator Development, NASA TP-1359, Dec. 1978.

QUESTION: Warren Campbell (BDM Corporation). Can you tell me what the minimum range of the AIM Doppler lidar is? What is your first range gate?

ANSWER: I think the minimum range was just a few meters off the launcher, but I'd have to check. The range went out to 700 but we had lots of measurements in close and spread them out in a geometric progression because we were interested in the close-in effects. We kept doubling where the gates were as we went out. The first range gate was at 10 m.

CAMPBELL: I have just one comment: I don't know how you will ever get around the problems you have with trees. Of course, the fetch downstream where the internal boundary layer is developing is felt a long way downstream and that depends on where you are.

DICKSON: I have seen some work where it was as much as 400 m. One of my suggestions was that we get lawnmowers and chainsaws and go upwind and clear everything out. I might add one other thing, since you mentioned the LDV, we did see missile wake turbulence effects with the LDV. Of course, the AIM was using a conical scan and a Fast Fourier Transform. The missile wake turbulence just blew the AIM off the air, but when we went back to the raw data we could see the missile wake turbulence and its decay. We weren't instrumented or looking for it, but it was definitely there, and I see LDV's as tools for examining missile wake turbulence in addition to turbulence around airports and other things.

QUESTION: Bob Heffley (Manudyne Systems). I have one quick comment. There is an Army ECOM report circa 1966 (TR-ECOM-6019) which describes boundary layer profiles below tree lines and various kinds of vegetation. This was based on both wind tunnel and full scale measurements.

STATE:

$$\begin{pmatrix} \bar{U} \\ U' \end{pmatrix}_n = \begin{pmatrix} 1 & 0 \\ 0 & \rho \end{pmatrix} \begin{pmatrix} \bar{U} \\ U' \end{pmatrix}_{n-1} + \begin{pmatrix} 0 \\ U'' \end{pmatrix}_n \quad , \quad U''_n \sim N(0,\, q), \quad q = \sigma_{U'}^2 (1-\rho^2)$$

OBSERVATION:

$$Z_n = (1,1) \begin{pmatrix} \bar{U} \\ U' \end{pmatrix}_n + V_n = U_n + V_n, \quad Vn \sim N(0,\, r)$$

PREDICTION:

$$E\,(U)_n^- = (1,1)\; E \begin{pmatrix} \bar{U} \\ U' \end{pmatrix}_n^- = (1,1) \begin{pmatrix} 1 & 0 \\ 0 & \rho \end{pmatrix} E \begin{pmatrix} \bar{U} \\ U' \end{pmatrix}_{n-1}^+$$

FILTER:

$$E \begin{pmatrix} \bar{U} \\ U' \end{pmatrix}_n^+ = E \begin{pmatrix} \bar{U} \\ U' \end{pmatrix}_n^- + \begin{pmatrix} \frac{1}{n} \\ \left(1 - \frac{1}{n}\right)\epsilon \end{pmatrix} \left[Z_n - E\,(U)_n^- \right]$$

$$\epsilon \simeq \frac{q}{q + r}$$

Figure 1. Discrete recursive filter.